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DEFECTS DETECTION AND CHARACTERIZATION USING LEAKY LAMB WAVE (LLW) DISPERSION DATA

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INTRODUCTION

Composite materials are being used at a significant level of usage for flaw critical structures and they are taking a growing percentage of the makeup of aircraft and spacecraft. Composite structures are now reaching service duration, for which the issue of aging is requiring adequate attention. The key to efficient inspection of composites is the ability to determine their integrity and durability. Standard NDE methods, which were developed to inspect metallic structures, were adapted by the industry for inspection of composites partially accounting for the multi-layered anisotropic nature of these materials. These standard methods provide limited and mostly qualitative information about the material properties and defects. The discovery of the ultrasonic LLW and the Polar Backscattering phenomena in composites [1, 2] established the foundations for quantitative NDE of these materials as well as the extraction of detailed information about flaws and material properties. These phenomena are based on obliquely insonified ultrasonic waves and numerous analytical and experimental studies followed the discovery of these phenomena [e.g., 3-5]. These studies led to the development of quantitative NDE capabilities of determining the elastic properties, characterize flaws, and even the evaluation of adhesive bonded-joints' quality [6]. In spite of the progress that was made both theoretically and experimentally, oblique insonification techniques are still mostly academic tools and have not yet become standard industrial NDE methods for composite materials. In the last several years, the authors have investigated the issues that are hampering the transition of the LLW method to the practical NDE arena and are making efforts to overcome the method limitations. This paper covers the progress that was made by the investigators in developing the LLW method for characterization of flaw that are related aging aircraft.

LEAKY LAMB WAVE PHENOMENON

The phenomenon of leaky Lamb wave (LLW) is induced and measured in plate-like solids using a pitch-catch ultrasonic setup that is immersed in fluid. The phenomenon is a resonant excitation of plate waves that leak waves into the fluid and interfere with the specular reflection. LLW was discovered in 1982 using Schlieren imaging system while testing a composite laminate at various frequencies [1]. Starting at the end of 1982, Bar-Cohen and Chimenti [1] made an extensive investigation of the LLW phenomenon characteristics and its potential for NDE applications. The initial efforts concentrated on experimentally documenting the observed modes and the effect of defects on the reflection spectrum. This effort was followed by numerous studies of the LLW phenomenon [e.g., 3-5].

The need for an effective data acquisition capability and accurate modeling of LLW was well recognized by the principal investigators Bar-Cohen and Mal. These investigators, who started their joint efforts in 1987, developed effective capabilities of experimentally recording the Lamb wave modes, accurately modeled the wave behavior and developed a method of inverting the elastic properties from the measured dispersion data [6]. Recently, the principal investigators enhanced their LLW test system to allow rapid acquisition of dispersion curves and improved the speed and accuracy of inverting the acquired data to elastic properties.

While the LLW method showed significant capability in quantitative NDE of composites it has not become yet a standard method. The authors examined the possible causes for this discrepancy between capability and applicability and identified several reasons, which are now being addressed. These possible reasons include:

a) Complex data acquisition - The LLW data acquisition experiment is complex and the related process has not been user friendly. On going efforts are made to improve the data acquisition process through integration of software and hardware and a significant progress was accomplished.

b) Material density - The inverted material constants are based on the assumption that the material density is known. NDE measurement of the material density can be done by radiography but this method is not practical and an alternative technique of measuring the density from a single side in real-time is needed. To minimize instrumentation complexity, preferably using ultrasonic testing.

c) Multi-orientation laminates - The inversion algorithm developed for the elastic properties determination has been very successful for unidirectional laminates. The analysis of laminates with multi-orientation layers using ply-by-ply modeling is complex and leads to ill-posed results. The authors are currently studying inversion methods that are not requiring to deal with the individual layers.

d) Time-consuming process - The baseline for dispersion curves acquisition is the capability of the JPL's LLW scanner sweeping through a selected spectral range. Acquisition of a dispersion curve for a single laminate point used to take between 10 and 20 minutes. Recent development by the authors allows a dispersion curve measurement at a rate of less than a minute for over 20 angles of incidence.

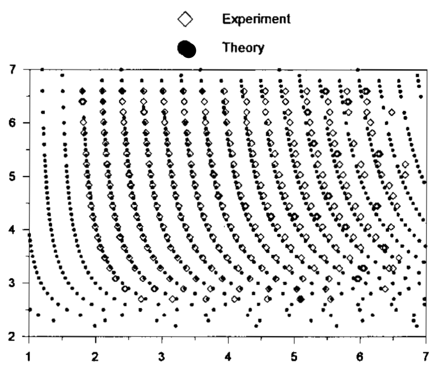

Figure 1: Dispersion data for a defect-free 16-ply unidirectional Gr/Ep laminate

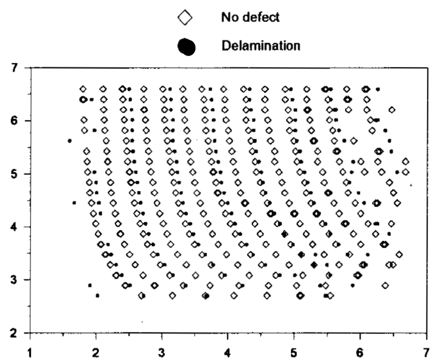

Figure 2: The effect of porosity layer (microballoons) between the 8th and 9th plies.

Note: *Thickness = 2.81 mm, Density = 1.588 g/cc and the inverted elastic properties* C_{11} *= 161.31 GPa,* C_{12} *= 6.10 GPa,* C_{22} *= 13.90 GPa,* C_{23} *= 6.53 GPa,* C_{55} *= 7.26 GPa*

Using the JPL's modified LLW setup dispersion curves were acquired to investigate the effect of defects. Of particular interest, the authors examined defects that are associated with aging aircraft and repaired structures, e.g., delaminations, porosity and fire damage. The reflection spectra were evaluated to identify the center of the specific flaws in order to obtain a typical representation of their dispersion curve response. In Figure 1, the reference experimental and theoretical dispersion data for a defect free laminate is shown. This laminate is a unidirectional 16-ply graphite/epoxy AS4-3501-6. Testing a delaminated area (simulated by a Teflon foil) showed a response that is typical to a thinner laminate and the depth of the damage can be determined from the spectral distance between the modes. Figure 2 shows the dispersion curve for a 16-ply defect-free area with a superimposed dispersion curve obtained from a delamination at half the thickness. As can be seen, the delaminated area behaves ultrasonically similar to a laminate that is half the thickness. A test of a simulated porosity layer at the middle of the laminate thickness shows different characteristics. At low frequencies the response of the porosity layer is similar to the defect free area, whereas at high frequencies the laminate respond similar to a delaminated area. This characteristic response is expected since individual pore is smaller in diameter than the wavelength, and therefore at low frequencies the material appears as a defect free while at short wavelengths the average porosity diameter approaches the wavelength in size. Testing an excessively heated area, which is the characteristics of fire damage, shows that the matrix dominated elastic constant C_{22} decreased with the increase in damage level. This result is consistent with the expected change to the matrix caused by excessive heating.

CONCULSIONS

Theoretical and experimental studies of the LLW phenomenon have led to a significant progress in understanding the wave behavior in composites. Effective analytical tools were developed for the inversion of data for material property determination and defect characterization. Further, unique experimental tools were developed for rapid and accurate data acquisition. In spite of this progress, the LLW method has not been widely adapted as a standard quantitative NDE method. The key issues, which affect the practicality of the LLW method, are being addressed by the principal investigators. A rapid, user-friendly data-acquisition system and improved analytical tools were developed to automatically determining the dispersion data and the inverted elastic constants. This development simplifies the process of flaw characterizing and the determination of material property degradation. The enhanced LLW system was used to characterize flaws that are potentially induced in service and unique signatures were identified for three different flaws including delamination, porosity and fire damage.

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